Strong spectral evolution during the prompt emission of GRB 070616

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Abstract. *Swift* has revealed features in GRB early light curves, such as steep decays and X-ray flares, whose properties are consistent with an internal origin though they are far from understood. The steep X-ray decay is often explained using the curvature effect; however a significant number of GRBs display strong spectral evolution during this phase, and a new mechanism must be invoked to explain this. Of particular interest are the longest duration GRBs in which the early emission can be studied in most detail. Here we present data for GRB 070616, in which the prompt emission shows a complex multipeaked structure, leading to one of the longest prompt emission durations ever recorded. We take advantage of extensive coverage of such a long burst by all Swift instruments. Combining data from *Swift* and *Suzaku* we study the evolution of the prompt emission spectrum, following the temporal variability of the peak energy and spectral slope.

Keywords: γ-ray sources; γ-ray bursts
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INTRODUCTION

The prompt emission mechanism for Gamma-ray Bursts (GRBs) is usually attributed to internal shocks due to collisions of shells of different Lorentz factors ejected from the vicinity of a compact object [1]. Though the general picture appears applicable to most GRBs, the details are far from understood and other models have also been proposed [see 2, and references therein]. The *Swift* mission has revealed complex early emission, as yet largely unexplained. The steeply decaying phases that directly follow both prompt emission and X-ray flares are often interpreted as due to the curvature effect [e.g. 3] where high latitude emission is delayed with respect to that on-axis. However, in this scenario significant spectral evolution is not expected but is seen in a large number of cases [4]. The longest duration GRBs provide rare opportunities to study the relationship between various possible early emission components. Very few GRBs are detected in γ-rays for more than 400 seconds when using the T_{90} parameter. Only $\sim$0.5% of the BATSE sample meet this criteria [5] and such GRBs remain rare in the *Swift* era.

Here we present *Swift* and *Suzaku* data for GRB 070616, whose $T_{90} = 402 \pm 10$ s is one of the longest on record. We study the evolution of the prompt emission through broadband lightcurves and spectra. Further details of this study can be found in [6].

RESULTS

Swift BAT triggered on a gradual rise of γ-ray emission which lasted approximately 100 s before the first and strongest peak, centred at T_0+120 s. Thereafter multiple blended

peaks continue the seemingly flat prompt emission in both γ-rays and X-rays out to T_0+500–600 s. At this point the γ-ray emission appears to return to the count rate at which it began at T_0, whilst the X-ray emission begins a very steep decay lasting until T_0+1200 s. Fig. 1 shows the joint BAT-XRT lightcurve in which peaks are temporally coincident strongly suggesting that the X-ray and γ-ray emission come from the same component. Contrastingly, the V band optical emission observed with UVOT is rising.

The BAT hardness ratio (50–100 keV/15–50 keV) remained approximately constant until T_0+285 s when the spectra softened significantly over the remainder of the γ-ray observations. The XRT hardness ratio (1–10 keV/0.3–1 keV) shows the same behaviour, with the spectral evolution beginning at $\sim T_0$+500 s. To examine the spectral evolution seen in the hardness ratios, we time-sliced the BAT and XRT data into 100s-long bins covering T_0+137–737 s. We adopted an absorbed Band function model [7], fixing the high energy power law slope to $\beta = 2.36$ as found in the *Suzaku* spectrum [8, 6, and adopting $F_\nu \propto \nu^{-\beta}$]. Intrinsic extinction was determined from fits to the X-ray data alone to be constant, amounting to a total Galactic+intrinsic absorbing column of $N_{\rm H} = 0.4 \times 10^{22}$ cm^{-2} (no redshift is available). The peak energy is derived from the free parameters α (low energy power law index) and E_0 (characteristic energy) using $E_{\rm pk} = E_0(2-\alpha)$. $E_{\rm pk}$ can be well constrained and is observed to move to lower energies with time from 135 keV down to 4 keV in $\sim$600 s, while the spectral slope α also varies gradually, softening with time, shown in Fig. 2.

DISCUSSION AND CONCLUSIONS

The lightcurve is atypical in that the emission rises relatively slowly over $\sim$100 s to a peak, then persists at a fairly constant level before showing a rapid decline. Strong spectral evolution is observed throughout the prompt phase. We are able to track the spectral peak energy as it moves from the WAM/BAT energies down to a few keV. At the same time we find a softening of the spectrum below the peak energy.

Spectral evolution through the prompt phase has been noted previously, and is inconsistent with the idea that the curvature effect alone is driving the emission during the steep decay [e.g. 9]. Using a curvature effect model to explain the steep decay in GRB 070616 we require that phase to begin at $T_0+632^{+11}_{-12}$ s requiring a long initial emission period of $>$600 s. The curvature effect is in fact a poor fit, but the combination of the curvature effect and the strong spectral evolution we observe may be able to account for the steep X-ray decay.

Only 25% of *Swift* GRB prompt X-ray tails can be fit with the curvature effect alone [4]; those not well fit show spectral evolution. From fits to 16 GRBs, [4] tested and subsequently disfavoured two possible causes of the spectrally evolving X-ray tails, namely an angle-dependent spectral index in structured jets and a superposition of the curvature effect and a power law decay component. The observed spectral softening could, they suggest, be caused by cooling of the plasma where the cooling frequency decreases with time. This manifests itself as a cut-off power law shape with the cut-off moving to lower energies with time, proposed for GRBs 060218 and 980923 and similar to our Band function results for GRB 070616. In this scenario the peak energy we track through the BAT band would be the cooling frequency. In addition we observe softening

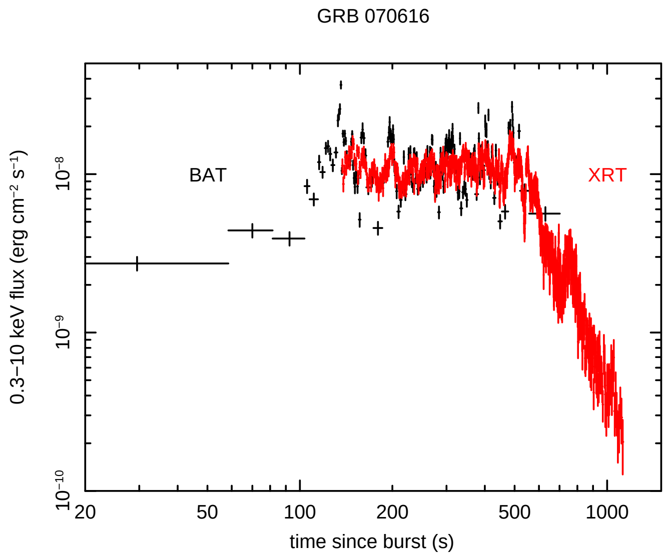

FIGURE 1. The joint BAT-XRT lightcurve (BAT extrapolated to the XRT band using multiple spectral fits) showing the coincidence of peaks, long-lived flat behviour and steep X-ray decline.

of the low energy power law slope which remains unexplained.

It is possible that we are observing a combination of components which together mimick spectral evolution. We investigated a scenario with two spectrally invariant power laws: the relative contribution of the softer power law to the total spectrum increasing with time. This is a viable explanation of the spectral evolution, but can be ruled out as it does not fit the lightcurve behaviour. We then applied the modelling procedure of [10, 11] in which it was shown that many GRB early lightcurves can be well modelled by up to two emission components each consisting of an exponential+power law decay. But again the prompt emission lightcurve of GRB 070616 is not well fit by this model. Interestingly, several, although not all, of the GRBs with strong spectral evolution studied in [4] are also not well fitted by the two-component lightcurve model [e.g. GRBs 051227 and 060614, see 11]. Others not well fitted by this type of modelling (e.g. GRB 051117A) were identified by [4] as having evolution which they attributed to flares. Such GRBs may instead be more similar to GRB 070616.

In conclusion, the prompt emission of GRB 070616 comprises a component well fitted with a Band function and a possible further component. The movement of the peak energy shows that great care must be taken when using average $E_{\rm pk}$ values. It is clear that both broadband coverage and good time resolution are crucial to pinning down the origins of the complex prompt emission in GRBs.

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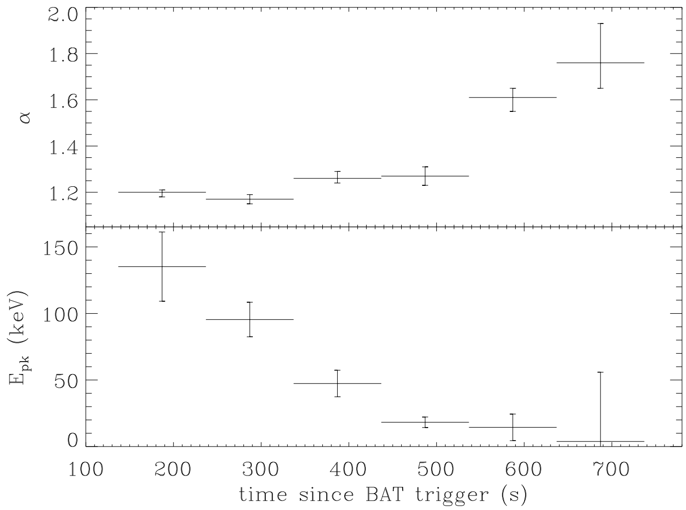

FIGURE 2. The variability of spectral slope α (upper panel) and peak energy E_{pk} (lower panel) in Band function fits to the early BAT-XRT spectra.

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